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REVIEW ARTICLE

Past, present, and future of the satellite-based automatic identification system: areas of applications (2004–2016)

Mélanie Fournier[1,2] · **R. Casey Hilliard**[3] · **Sara Rezaee**[1] · **Ronald Pelot**[1]

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Abstract

In 2016, the world shipping fleet grew by 3.5%. Even if the annual growth rate remains at its lowest since 2013, the global situation is still in overcapacity (UNCTAD 2016). Ninety percent of global trade, by volume, is done by sea. Monitoring this fleet helps with vessel navigation, informing to help avoid critical situations such as collisions, accidents leading to oil pollution, grounding, or ships in distress, but also because traffic management in congested areas is essential. For system wide management, in regions such as MPAs (marine protected areas), conservation is the key factor, and movements can be monitored and analyzed in order to determine illegal or suspicious activities, or in order to limit and/or divert traffic, to mitigate the risks to species subject to protection. It is among these efforts that the automatic identification system (AIS) can play a key role. Since 2004, this VHF transceiver-based reporting system, imposed by the International Maritime Organization (IMO), has shifted from a traditional vessel identification device to a tool used in a wide variety of applications. The most common uses are safety and security; these issues are quite visible in the media and may touch more people on a global scale (e.g., piracy, oil spills). Over the years, AIS has become, especially with the emergence of the satellite-based capture of the signal in 2011, a widely used tool for developing applications such as fisheries monitoring, marine conservation, air pollution forecasting and modeling, ballast water monitoring, invasive species transport, and many more. In this paper, we propose to review the peer-reviewed publications related to the uses and applications of the AIS.

Keywords AIS · Satellite-based AIS · Literature review · Safety · Security · Marine environment

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✉ Mélanie Fournier

Extended author information available on the last page of the article

1 Introduction

In September 2015, in Halifax, Nova Scotia, a workshop on automatic identification system (AIS) applications and data management techniques was organized by the Canadian NCE MEOPAR (Marine Environmental Observation Prediction and Response) and one of its Canadian-based partners, exactEarth Ltd (MEOPAR and exactEarth 2015). The workshop's aim was to communicate current techniques and approaches for handling AIS data for the purpose of analysis and use in the maritime domain. In preparation for the workshop, a search was undertaken for a holistic review of applications that have used AIS data since it became mandatory (for specific sizes and types of ships (IMO 2000)). Military and research organizations have published literature reviews or reports about AIS progress generally, and more specifically about satellite-based AIS (Hoye 2004; Skauen 2016), the algorithms developed to detect ships (Shaileshbhai and Brahmbhatt 2016), and the integration of synthetic-aperture radar (SAR) and AIS (Zhao et al. 2014); however, we did not find a comprehensive overview of the many uses and fields in which the AIS has been, and is being, used.

1.1 AIS overview

In 2000, the International Maritime Organization (IMO) revised Chapter V of the Safety of Life at Sea Convention (SOLAS) (IMO 2000). In order to limit the risks of collisions and grounding, a transponder[1] and communication protocol called automatic identification system or AIS became mandatory for a large portion of the commercial shipping fleet by the end of December 2004. As all ships are not subjected to this "Class A" AIS scheme, the IMO developed "Class B" AIS, that any ship may operate on a voluntary basis. The AIS is a device, which, in its most common form, sends and receives information from a ship to other ships and to coastal authorities according to the AIS protocol.[2] The system is mainly used for detection and identification of ships, as a complement to radar. The first publications about the device that we found, from the beginning of the 2000s, are oriented towards safety of navigation and the risk of collision (US Coast Guard 2000; Berking and Pettersson 2002; Berking 2003; Stitt 2004). These papers investigated the implications of the emerging AIS: "Will it replace the radar on the bridge?"; "Is there a risk in relying only on the AIS signal and ignoring radar?"; "What about training the crew on entering data properly or in a way that would limit errors?" Soon afterwards, authorities and research centers focused on the potential of such a device to improve the safety and the security of navigation through ship tracking. As the ship-to-ship signal is limited to 20 nautical miles typically, and the shore-to-ship signal is limited to 40 nautical miles, the military and maritime spatial researchers, as well as industry, began (circa 2004) to develop a satellite-based observation approach in order to increase the geographical range over which ships could be

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[1] It should be noted that the term "transponder," used here and in general literature to refer to the AIS hardware units, is not technically correct. A transponder is an automated transceiver that emits a coded identifying signal in response to an interrogating received signal. AIS units have functionality far beyond this definition and may be more appropriately termed "VHF transceiver-receptor(s)." In the interest of not confounding the reader with a new and unfamiliar term, we have elected to retain the term transponder while annotating this issue.

[2] Recommendation ITU-R M.1371-5, currently in version 5 at the time of writing (https://www.itu.int/rec/R-REC-M.1371/en)

detected. The Norwegian Defence Research Establishment (FFI) conducted one of the first published feasibility studies about the capabilities of satellite-based AIS (S-AIS), promising a long-range tracking capability (Hoye 2004; Eriksen et al. 2006). Concurrently, a European consortium led by Telespazio, and partially funded by the European Space Agency (Scorzolini et al. 2010), reported on a European study of a space-based AIS receiver. Following the pioneering S-AIS receiver launches between 2007 and 2010, the first reports and papers on the behavior of the satellite-based AIS signal capture were published. FFI initially (Helleren et al. 2008; Eriksen et al. 2010), followed by the German OHB (te Hennepe et al. 2010), published about the first years of operation and the capability provided to authorities for thus monitoring the world fleet.

1.2 Satellite-based AIS

"The user feedback indicates that now that the light has been switched on, no one wants to go back into the dark" (Skauen 2016). This sentence highlights what satellite AIS brought to authorities: a high rate of detection in areas that were completely outside of coastal range, among other things. To give the reader an example, in 2004, when the AIS became mandatory, the system was designated with theoretical capacity for up to ~ 4000 ships, with a probability of detection of essentially 100% (barring poor configuration), constrained to a range of ~ 40 nautical miles from the receiver. The study published by FFI (Hoye 2004) reported a space-based system that could handle up to 3000 ships with a detection rate better than 99% for 15 min of observation, and more than 10,000 ships for 60 min of observation, while scanning a swath of ~ 1400-nm radius. In 2010, researchers with Astrium Services/Spot Infoterra (de Saint Vincent 2010), investigated S-AIS performance limitations, especially the detection rate. They showed that the refresh rate and the number of satellites and ground stations available would be key factors in the development of space-based AIS and its capabilities. Six years later, Hilliard made an estimation based on an exactEarth dataset over a recent month in 2016 and estimated that via satellite AIS, approximately 50,000–60,000 MMSI (Maritime Mobile Service Identity)/vessel detections are noted daily, corresponding to 150,000–200,000 annually, but controlling for errors these represent approximately 30,000–45,000 actual vessels daily, and between 100,000 and 180,000 vessels yearly.[3] This is consistent with exactEarth-stated data service, compiling over 7,000,000 AIS messages daily, and growing.

At the time of writing, three AIS-observing constellations, comprising ~ 60 total satellites, along with ~ 10 individual satellites are operational and used for maritime AIS surveillance (a table of all known at present is include as Annex 1). Dozens of companies are providing satellite-based AIS data, though a significant proportion resell data licensed from the two largest constellations, operated by exactEarth Ltd. and ORBCOMM.

By 2007–2008, global AIS coverage has allowed authorities to track ship movements and, accordingly, has revolutionized the maritime surveillance and continues to do so as the system is employed for an increasing number of applications. Nevertheless,

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[3] exactEarth documents an approximately 165,000 vessels total observed, ORBCOMM 150,000, and LuxSpace 100,000 (in 2016).

some challenges persist, most notably reception of the lower powered AIS-B transponder signals, desired improvement (reduction) of satellite revisit time to more closely approach the full reporting rate afforded by AIS, and general improvement of the quality (i.e., accuracy, currency) of data entered into the system.

1.3 Methodology

The IMO references on its website the following categories of focus: marine environment, safety, and security (IMO 2017a, b, c). Each category is subdivided into several topics of concern: pollution prevention and response, navigation, communication, piracy, unlawful acts, ballast waters, etc. Our literature review has been structured to generally follow these categories and topics. Figure 1 represents categories and topics as described by the IMO that we retained for our review. Topics were included that had been addressed in at least one referenced paper, and that linked directly to AIS and its applications. We added to the three main categories a fourth one, which we termed “techniques,” which groups the papers on modeling, visualization, and simulation involving AIS that have an impact across the topics studied. In cases where a paper applies a modeling technique falling directly in one of our topics, we decided to keep the paper in the respective section (rather than the techniques section). Since the marine environment encompasses a variety of key issues, we thought that each was best served by their own section. This was the case for fisheries monitoring, noise, ballast water, marine mammal strikes, and oil spill monitoring.

1.4 The literature review

Our team has complementary sets of knowledge in terms of maritime surveillance and AIS applications: risk analysis, data fusion, fisheries monitoring, pattern and trajectory analysis, noise modeling, and data science. The review was conducted in four steps. We started our review by identifying the publications, ranging from peer-reviewed publications to technical reports, in our specialties. Then, in order to supplement our ability to scan the literature efficiently, we used an open-source software called *Carrot2*. This

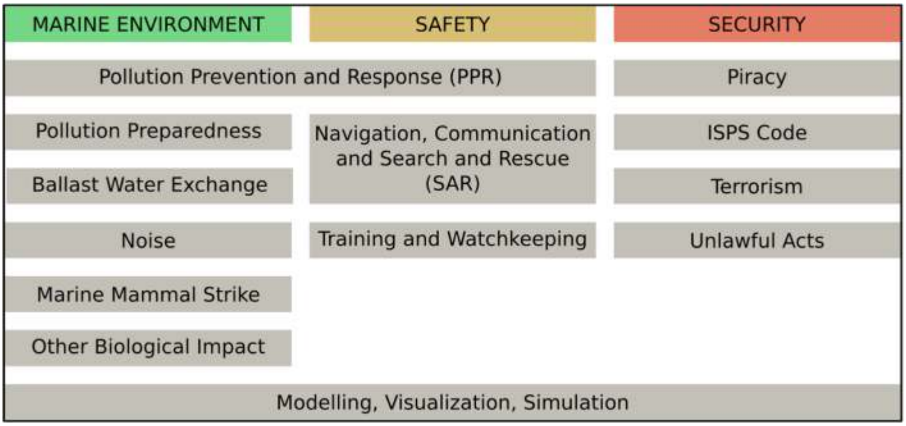

Fig. 1 Main topics of our review, using select IMO categories, extended by ours

search engine helped us to cluster the results into thematic categories. In a third step, we cleaned the results by removing duplicates and setting aside the gray literature (websites, non-peer-reviewed papers) unless exceptionally relevant. Finally, for each discovered paper, we analyzed the references, removed further duplicates (since some papers that span topics were collected through different searches), and gathered the results by topic in a spreadsheet. In total, we reviewed 204 papers and reports. Table 1 summarizes our results and the structure of our paper.

Our review deliberately omitted some topics such as air emissions, shipping economics, computer science, and signal processing, incorporating only the subjects in which we have skills and knowledge.[4] In a final step, we analyzed trends among the research community over the years. However, due to the large amount of data produced, we deemed it more appropriate to present the results in another publication.[5] Nevertheless, there is one aspect that we retained for this literature review: annotation of emerging topics such as the human factor contribution to errors found in AIS data, and "spoofing" to conceal vessel operations or behavior, which we noted also as having appeared in the literature since the inception of the AIS. Now that the scale of monitoring has expanded, the number of both involuntary and voluntary errors increased significantly, though data quality assessment was already identified as an issue at the beginning of the 2000s (Junzhong 2004; Mokhtari et al. 2007). However, given the elapsed time and rapid maturation of the system, the human factor analysis made in 2007 by Harati-Mokhtari et al. should be reassessed with the satellite-based AIS in order to see if the same fields are subject to the same rate of errors.

In this paper, we first review the work published on AIS applications dedicated to marine environmental protection and follow with the traditional or more popular topics of safety and security. Finally, we review the techniques applied to processing AIS data, which can have applications and benefits over a large range of fields. We identified four domains in which we know the AIS is utilized but which we did not survey in detail for this paper: (1) air pollution/emissions, (2) economics (determining the efficiency of routeing and traffic planning), (3) computer sciences, and (4) signal processing. Nevertheless, we provide a brief overview of these important topics next, grouping domains 3 and 4 since they are linked in most of the papers we located. We have, however, compiled some (non-exhaustive) reference information that were gleaned from our search in Annex 2.

2 Marine environment applications

On October 2016, the 70th IMO Marine Environment Protection Committee (MEPC) meeting took place in London, UK. The topics addressed included garbage, harmful aquatic organisms in ballast water, air pollution and energy efficiency, protection of special and sensitive areas, and pollution prevention and response (Lloyd's Register

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[4] See Annex 2 for more information on these particular topics.

[5] A second publication will be published on the trends over time for the AIS uses and applications. We used bibliometrics techniques to study the evolution of interests and the inter-connections across the relevant research communities.

Table 1 Summary of the papers compiled for our review

Main category	Topics	Number of publications reviewed
The value of AIS data from a marine environment viewpoint (chapter 1)	Fishing management (Section 2.1): - AIS as a monitoring data source vs. VMS - Automatic detection of fishing areas/craft - Mapping fishing effort - Need for integrated framework - Illegal fishing	11
	Oil spill monitoring (Section 2.2): AIS as a data source for: - Risk analysis - Traffic simulation - Illegal discharge	7
	Ship noise pollution (Section 2.3): - Mapping of ship sound - Harm to mammals - Estimation of noise level - Propagation of vessel noise - Ground-truthing capabilities - AIS as an aid to discretizing vessel noise	31
	Species at risk (Section 2.4): - Strike risk - AIS as a warning system for whale sightings areas	21
	Other biological impacts (Section 2.5): - AIS for MPA (marine protected area) compliance observance - Ballast water and invasive species - Anchor scour - Plastic and marine debris	25
Marine safety (chapter 2)	- Collision and grounding risks assessment (Section 3.1) - Traffic simulation (Section 3.2) - Small craft issue (Section 3.3)	40
Security (chapter 3)	- Maritime domain awareness - National security - AIS analysis for counter-piracy operations	12
Techniques (chapter 4)	Satellites for AIS	5
	Data fusion	11
	Marine traffic pattern analysis, prediction, anomaly detection	27
	Data quality	20
Total papers reviewed	204	

2016). For our review in this category, we consider these six areas and add fisheries monitoring and noise modeling, as well as marine mammal strike risk.

2.1 Monitoring, characterizing and protecting fisheries, species, and stocks

Given that the AIS' main purpose is safety, it was not designed to address fleet monitoring nor fisheries management. Moreover, carrying an AIS was not mandatory for fishing vessels in any country until 2014. Since then, the EU has required that all vessels greater than 15 m carry AIS on board, including fishing vessels. A US regulation made AIS mandatory for fishing vessels greater than 20 m in 2015. AIS is not compulsory for fishing vessels in Canadian waters; however, Transportation Safety Board of Canada (TSB) reports show that many Canadian fishing vessels carry AIS devices on board even in the absence of a legal requirement (TSB 2012). Despite the uneven AIS coverage of fishing vessels, several research studies have started to use AIS data as an input for fishing monitoring systems. In the following section, studies are presented showing the application of AIS to explore: (1) fishing activities and efforts, (2) illegal fishing, and (3) comparison with vessel monitoring systems (VMS).

2.1.1 Fishing activities and efforts

Up to the present time, the most common monitoring data source for fishing vessels has been VMS data. Russo et al. 2016 compared AIS and VMS data sources to map fishing efforts of the Italian fishing fleet in the Mediterranean Sea for the year 2012, which showed that VMS has a better spatial coverage than AIS but also that it is less frequently reported. The work concluded that AIS has better nearshore performance but that it might underreport offshore activity. It was also concluded that land-based AIS will underrepresent fishing activity in deeper water. This may be due to fishers turning off their AIS for commercial/privacy reasons and/or limited range of the receivers. This information reliability is further compounded by the fact that fishing effort distribution is a complicated function of stock location, bathymetry, weather, etc.

Notwithstanding the previously outlined fishing vessel carriage limitations regarding AIS, several recent studies have used S-AIS as the main source of fishing/fishing vessel monitoring data.

One of the first studies in this area was conducted by Mazzarella et al. 2014. To automatically detect fishing areas using AIS, they presented an algorithm in four main steps: (1) pre-processing, (2) trajectory extraction, (3) event detection (stop or move), and (4) clustering. Changes in speed and direction of trajectories are used as indicators of vessel status (stop or move). A similar approach has been described in 2015 (Cazzanti and Pallotta 2015) to identify and characterize main stationary areas for vessels. They developed an algorithm to detect vessels' status as "sailing" or "stopped" using AIS data. Clustering methods are then used to determine the generalized stopping areas for vessels and/or to detect anomalies. If the identified stop area is not a port or harbor and it is far from coastline, it is asserted to be a fishing area.

From a National Defence perspective, Canada is trying to improve situational awareness in Baffin Bay. In the region of interest, SAR imagery was the main source of data used for vessel detection; however, due to the limited number of vessels and large number of icebergs in the area, the distinction between the two is a challenge; Horn (2015) illustrated how S-AIS could help to identify fishing patterns in the area. The outcomes generated could then be used for prediction and decision support in case of anomalies.

The work by Natale et al. 2015 sought to produce a high-resolution fishing effort map in the EU. Though AIS is mandatory for all vessels in the EU greater than 15 m, the primary goal of AIS is safety (not enforcement); therefore, a concern was posited that the coverage of fishing vessels might be discontinuous and not sufficiently robust to describe their operational extent. The approach first matches AIS with a fleet registry, identifies fishing and non-fishing behavior based on the number of speed changes and frequency of distinct speed levels, and then compares these with detailed logbook entries of matched vessels. The results showed that, despite the problems in coverage, AIS could still be used as an efficient source to map fishing efforts.

Another application of AIS data to better map fishing efforts is to distinguish fishing and non-fishing behavior. de Souza et al. 2016 used AIS to automatically detect fishing and non-fishing behavior for trawlers, longline, and purse seine fishing gear types. Vessel tracks are built from AIS data and subjected to expert labelling to differentiate between periods of potential fishing and non-fishing behavior. Hidden Markov modeling, data mining techniques, and multi-layered filtering are used to automatically detect fishing activity with distinctive models for the different gear types. The study scope in this widely applicable work was worldwide over a study period of 2011–2015, and their work was published in 2016.

To achieve a better understanding of fishing efforts, S-AIS, VMS, and other data sources such as SAR imagery should be integrated into a unified framework; however, this type of integration has significant technical and administrative challenges to overcome (Greidanus et al. 2005; Ozturk 2013). An ongoing project started in 2011 aims to design an information system to integrate AIS, S-AIS, VMS, SAR, underwater acoustics, pressure and electromagnetics, ship-based and coastal radar, and ship registries to detect and identify vessels. This project comprises four main phases including processing and analysis, data fusion, construction of results databases, and reporting/feedback mechanism (Renga et al. 2011).

2.1.2 Illegal fishing

Various local situational factors may affect illegal fishing. The Pasta-Mare project[6] investigated these factors in 53 countries, including Canada. One of the variables used in their model was "detectable fishing vessels." The source of this data was the location of 6000 vessels during the year 2010 extracted from satellite and terrestrial AIS; however, the results of this study showed that the number of fishing vessels detected in an area does not statistically correlate with illegal fishing probability (Petrosian 2015).

2.2 Oil spill monitoring

AIS has gradually become one of the main data sources for marine oil spill monitoring. Schwehr and McGillivary (2007) discussed the different ways that oil spill analysis can benefit from AIS data sources, identifying:

1. Risk analysis: as a direct way to identify high- and low-risk areas for ships and consequently reduce and prevent the risk of shipping accidents which may lead to oil spills.

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[6] Preparatory action for assessment of the capacity of spaceborne automatic identification system receivers to support EU maritime policy. For more information, refer to Pasta Mare Technical Proposal Call for Tenders No MARE/2008/06.

2. Response time: information on traffic flows and location of oil spill incidents can provide relevant agents with real-time positions of incidents and reduce the overall response time.
3. Identification: AIS can be helpful in detecting and identifying responsible vessels in case of illegal oil discharges. Several works in this area are presented under the section "Illegal Discharge."

2.2.1 Risk analysis

As stated earlier, AIS was designed to identify ships and therefore limit the risk of ship collision, and to complement radar to that effect. AIS data has been, and still is, widely used in probabilistic approaches, statistical analysis, and mathematical modeling, as an input to quantitative models aimed at estimating the risk of collision incidents. In 2007, Eide et al. proposed two probabilistic models to estimate the risk associated with oil tankers. The first project (Eide et al. 2007a) aimed to determine which individual oil tankers are most likely to produce oil spills and the likelihood of spill occurrence. The model extracts relevant information, such as position and identity of each oil tanker ship passing the Norwegian Coast, from an AIS database and links this information to other sources. The individual risk levels for each ship are calculated from this fused dataset. Collision is not the only maritime safety threat to incur risk of oil spill, as grounding also represents a major hazard potentially leading to spilled oil. Their second project (Eide et al. 2007b) served to develop a model that focuses on the surroundings of transiting oil tankers, using real-time AIS data. This model estimates the probability of drift grounding in real time and combines it with the impact of a spill on the receptors. Montewka et al. (2011) presented a mathematical model to analyze the risk of collision and grounding of oil tankers in Gulf of Finland under ice-free conditions. They developed a mathematical ship motion model, assuming non-homogeneous traffic flow, to estimate collision risks. To describe the case of grounding incidents, they assumed that ship and navigational obstructions are interacting objects and adopted a gravitational model to estimate the risk.

2.2.2 Traffic simulation

AIS data can be used as an input in choosing sailing routes. This approach was adopted by Akhtar et al. (2012) to identify safe sailing routes for heavy ships (greater than 5000 Gross Tonnage) along the Norwegian coast. The result of traffic simulation and incidents projected for the year 2025, using AIS to inform sailing routes, showed a decrease by 590 tons per year in spill amount compared to the year 2008.

2.2.3 Identification of illegal discharges

AIS data is now commonly used to backtrack traffic patterns and detect vessels that could be responsible for the discharge of a detected oil spill (Uiboupin et al. 2008; Ferraro et al. 2010). An alternative approach is to detect a vessel responsible for an oil spill event based on the assumption that all vessels pollute along their track. This method uses AIS data to simulate pollution tracks and then compares them with the detected spill to determine polluter candidates (Longepe et al. 2015).

2.3 Ship noise pollution

Hydrophones have been used for the detection of a wide variety of underwater sounds since their conception during the latter part of WWI. Detection of sounds emitted by marine mammals dates back to the 1950s (Schreiber 1952), eventually leading to studies in the 2000s which indicated (Evans et al. 2001) that the acute pulses from Navy sonar were capable of causing direct harm to aquatic mammals. Presently, research seeks to explore and quantify the impact of persistent, anthropogenic noise in the marine environment which falls within the range of audibility for marine fauna (Clark et al. 2009). Ship-derived noise has long been identified as the most dominant anthropogenic (Wenz 1962) contributor to ocean noise; correspondingly, AIS has played an important role in facilitating estimation of the extent, quantity, and impacts of this "new pollution." Within this general schema, vessel emitted and received noise levels, propagation of noise fields, vessel acoustic locating, and vessel emission categorization have all been given treatment using AIS as a critical component of analysis, as outlined here.

2.3.1 Ship-source noise level estimation using AIS

Estimation of the source levels of sound emitted by vessels has been a key goal of much of the acoustic research using AIS. It has generally been asserted through ongoing research that the most pragmatic means of quantifying vessel sound is to opportunistically capture noise via a stationary hydrophone (or network of hydrophones), and then make inference about the vessel noise emissions at source. AIS data have been used to "pin down" the emitter location while acoustic modeling is applied to received signals in consideration of these locations. This approach has been utilized to underpin source level estimation techniques including matching of vessel closest point of approach (CPA) to sound pressure level (SPL) peak (Coward 2013), wide and narrow band range frequency assessment in presence of vessels (Garrett et al. 2016; McKenna et al. 2013; Veirs et al. 2016), receptor (i.e., marine organism) weighted source level assessment using geometry between vessel and receptor (Bassett et al. 2012; Bassett 2013; Fouda 2012), and adaptive thresholding to remove non-vessel noise (Merchant et al. 2012a, b). Refinements on source characterization have been made to leverage AIS-described characteristics to determine vessel parameters contributing to emissions (Erbe et al. 2015; Hatch et al. 2008; Listewnik 2014; McKenna et al. 2013; Veirs et al. 2016) and characterizing changes to source levels based on steaming speed vis-a-vis "slow steaming" initiatives (Leaper et al. 2014).

2.3.2 Ship noise emission received level assessment

While vessels' source noise levels describe the per-unit component of sound emissions, received noise from a remote location allows review with respect to receptors without addressing the relatively complex sound level loss modeling. In these instances, AIS data are employed to identify vessel presence at a more holistic level. Using this approach with AIS data, progress has been made in quantifying general loss of communication space by organisms of concern (Erbe et al. 2012; Fouda 2012; Hatch et al. 2012; Merchant 2014), and towards the general effects of regulatory and economic drivers to regional noise levels (McKenna et al. 2012a, b; Merchant et al. 2014). An alternative tack taken by McKenna (2011) has been to assess direct noise effects relative to individual organisms and their behaviors.

2.3.3 Ship noise field propagation

As a corollary to individual vessel's noise assessment, the development of general model forms of vessel noise have also been drafted using AIS, specifically the propagation of vessel noise within generalized zones of interest. This work includes predictive modeling of noise fields, incorporating vessel traffic information from AIS (Gervaise et al. 2015). A branch of this work explores the masking effect of the noise field with respect to biologically critical frequency bands used by whale (Hatch et al. 2012; Maglio et al. 2015) and porpoise (Erbe et al. 2014) species as exemplars. This differs from other works in that (a) a wider area is considered, and (b) only the acoustic masking behavior of biologically relevant frequency bands from vessels is considered. A second avenue of work here augments modeling by clarifying the implications of shallow water for vessel-to-animal noise interactions (Hermannsen et al. 2014; Sertlek et al. 2016).

2.3.4 Hydrophone array-based ship detection

Much of the acoustic research explored draws on a single hydrophone source for noise characterization; however, a limited number of multi-receiver applications were found with unique applications of AIS data. Of particular interest, as it may have implications for ground-truthing capabilities, is the study by Verlinden (2014) which uses multiple hydrophone returns to detect vessels. This approach has also been further refined by Santoz-Dominguez (2016), using AIS data to directly trigger a hydrophone recording, or conversely a detected noise signal inferring ship presence. This gives a "two-way mechanism" which could be applied to perform cross-validation between these data sources.

2.3.5 Vessel noise identification and classification

AIS data have been used to aid in discriminating vessel noise among other noise sources. Efforts have been made to develop a catalog of vessel noise emissions, tied to AIS identifications in order to characterize vessels over repeated observations (SOUNDMAP (n.d.); Santoz-Dominguez 2016; Scheer and Ritter 2013; UVigo n.d.; Veirs et al. 2016). Work by Ryan et al. (2013) has proceeded using methodology similar to the other vessel cataloging efforts, but also incorporating techniques to remove background noise from the primary vessel signal, using AIS data to assert vessel presence/absence in individual samples. This stream of work has also included efforts to model noise emissions by vessel classes indicated by AIS (Erbe et al. 2015; Hatch et al. 2008; McKenna et al. 2012a, b; Scheer and Ritter 2013; Veirs et al. 2016).

2.4 Marine mammal strike risk

Recent research has identified that, for a number of marine mammal species, vessel strikes can represent a significant proportion of the species' mortality events (Campbell-Malone et al. 2008; Berman-Kowaleweski et al. 2010). These studies include a number of species at risk and, in some cases, mitigation of such events could mean the difference between population collapse and recovery (e.g., North Atlantic Right Whales, as discussed by Caswell (1999)). For these reasons, AIS data have become an increasingly relied-upon resource as biologists seek to better explore the spatial relationship between marine mammals and vessels.

2.4.1 AIS and strike risk

Explanatory studies in this research area have considered simple coincidence assessment between vessels and marine mammals' habitats to qualify the problem scope. These have, for the most part, comprised general areal comparison between known habitats and trafficked areas (Aker 2012; Fais et al. 2016; Webb and Gende 2015). Expanding on this concept, other groups (Dransfield et al. 2014; Jensen et al. 2015) have looked specifically at traffic lanes (considering their usage rates via AIS), comparing the lanes with habitats to determine whether conservation might be better served by modifications to the traffic lanes. Marine mammal sighting data have also been used for comparison with AIS, where available, in place of generalized habitat information (Chion et al. 2012; Guzman et al. 2013; Lagueux et al. 2011; Priyadarshana et al. 2016).

Spatial risk assessment treatments of AIS vessel traffic data with respect to marine mammal strikes have been computed along two general themes. One approach has been to utilize absolute areal risk assessments, along administrative or geographic bounds, characterizing routes and vessels' attributes according to the risk presented to marine mammals which stray into these areas (Conn and Silber 2013; Wiley et al. 2011; Williams and O'Hara 2010; Williams et al. 2015). The alternative approach has been to address the strike problem with reference to the biological/habitat perspective, identifying the degree to which AIS-indicated traffic falls within the habitat areas (Betz et al. 2011; Chion et al. 2012; van der Hoop et al. 2012; Webb and Gende 2015).

2.4.2 AIS warning system development

A complementary "AIS-technical" research stream uncovered in the review proposes a new application of AIS to lessen vessel/mammal strikes. It has been suggested (McGillivary et al. 2009; Wiley et al. 2015) that whale sightings may be communicated directly to vessels via an AIS-directed message when the vessels are in, or approaching, an affected area. The feasibility and practicality of this concept has also been explored in operator surveys (Hovey 2015; Reimer et al. 2016).

2.5 Other biological impacts

Though materials relating to fishing, spills, whale strike risk, and noise effects on biological receptors represent the bulk of the uses of AIS that we surveyed with impact on the environment, there were a number of other novel applications which warrant mention here. We feel that these use cases represent interesting applications which are able to exploit AIS to obtain information unlikely to be captured in alternative data sources.

2.5.1 AIS for MPA compliance observance

The International Union for Conservation of Nature (IUCN) defines an MPA (Marine Protected Area) as “A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.” In areas where these spatial conservation measures (MPAs, but also voluntary Area To Be Avoided measures, etc.) have been put in place, studies have also made use of AIS to evaluate compliance. These evaluations have ranged from counting crossings considered to be taken in violation of such areas (Agardy et al. 2007; Scheer and Ritter 2013; Silber and Bettridge 2010) to considerations of speeds through speed-restricted areas to determine compliance at a more nuanced scale (Coomber et al. 2016; Lagueux et al. 2011; McKenna et al. 2012c; Scheer and Ritter 2013; Silber et al. 2014; Vanderlaan and Taggart 2009). Contemporary work by McCauley et al. (2016) has used AIS directly for fishing conservation efforts. Their paper demonstrates how marine governance can be strengthened by using AIS data in support of improving monitoring, tracking illegal fishing, and biodiversity conservation. Two articles were also located which contained insights from both legal (Delfour-Samama and Laboeuf 2014) and practical (Garrison and Rollison 2015) perspectives on the feasibility of using AIS as a tool for compliance (and enforcement), considering the limitations inherent to the protocol and its application. Compliance has also been measured in a voluntary context within a strike and acute noise impact mitigation strategy producing results and a process which may be useful for further work in this area (Chion 2011; Chion et al. 2012; Lagueux et al. 2011; McKenna et al. 2012c; Silber et al. 2012; Vanderlaan and Taggart 2009).

2.5.2 Ballast water and invasive species

Aquatic invasive species are a global problem, linked to international shipping, through ballast water, onboard shipped cargoes, and hull fouling. For this reason, analysis of global (satellite) AIS data is a potentially valuable resource for this area of study. However, most studies which addressed this topic had areas of limited spatial scope (Gollasch and Leppäkoski 2007; Mjelde et al. 2014; Seebens et al. 2013; Shucksmith and Shelmerdine 2015; Tidbury et al. 2016). We only uncovered a single instance, by Kaluza et al. (2010), in which invasive species were treated globally, using AIS as a basis for assessing traffic patterns. We were surprised by this result and expect to see more works like this in the future, perhaps as satellite AIS data become more accessible to researchers in this field.

2.5.3 Anchor scour

Analysis of anchor scour was noted in a handful of references (Davis et al. 2016; Tuck et al. 2011), as another application area in which AIS data provides a key piece in the analysis process. Given that the positioning data required to estimate anchor drag are unlikely to be available via any other avenue, this was considered an interesting topic of study.

2.5.4 Plastic and marine debris

Marine debris, much like aquatic invasive species, is an international concern with a component of exposure associated with marine traffic. In this regard, AIS analysis has a critical role to play, and several contemporary publications were identified (Liubartseva et al. 2016; Lozoya et al. 2015) using AIS to address this problem.

It is clear that the AIS data have a role to play in quantifying the degree of exposure that marine areas have to vessels. The availability of this exposure measure permits consideration of the potential effects which can range from literal impacts between vessels and organisms to more complicated impacts such as acoustic emissions. In the next section, we will address a more traditional use of AIS, maritime safety.

3 Maritime safety applications

Considering its origins as a tool to detect and identify ships, it is not unexpected that a large body of literature availing of AIS data has safety as a focus (118 papers discovered). AIS data are particularly useful in high-density areas where poor navigation practices, risky behavior, and/or hazardous conditions can quickly escalate into major problems. Since the terms safety and security are often misused and confused, it is difficult to separate them as publications and gray literature concatenate these topics under the general concepts of traffic management, maritime surveillance, maritime domain awareness (MDA), or maritime situation awareness (MSA). We have attempted to keep them separated, with topics of risk avoidance calculation, safety assessment, search and rescue, and response to marine pollution all designated as maritime safety. However, we treated the oil spills and related concerns under our marine environment section. Regarding domains such as data fusion[7] found in the safety papers, roles of nano-satellites for maritime surveillance purposes, traffic patterns, and network analysis, as well as data quality assessment, we reviewed in Section 5 of this paper. The chapter "Techniques" was judged more appropriate to this last category of papers as they are not solely dedicated to safety but are used for several applications.

3.1 Collision and grounding risk assessment

Though AIS data are now well integrated in traffic management systems, this was not the case at its inception (Harre 2000; Creech and Ryan 2003; Felski and Jaskolski 2012a), in spite of coastal authorities' desire for accuracy in their real-time (RT) surface picture. The historical data have proven in many studies and simulations that AIS has the potential to improve navigation management in high-density areas, port areas, and

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[7] Most often referring to ship detections using synthetic-aperture radar (SAR); electro-optical imagery, fused with AIS tracks alongside long-range identification and tracking (LRIT) data; vessel monitoring system (VMS); and radar.

coastal approaches (Tsou 2010). Probabilistic assessment, statistical analysis, mathematical models, and fuzzy logic have been widely used in order to estimate the frequency and the risk of collisions and/or groundings in specific maritime areas.

In Kujala et al. 2009 AIS data were used to calculate the probabilities of ship collisions in the Gulf of Finland and validated their model using historical incident data. Goerlandt and Kujala (2011) used AIS data to simulate traffic routes including the number of vessels, departure times, vessel dimensions, and sailing speed as real-world input to a model to estimate the frequency, time, and the location of collision incidents in the Gulf of Finland. With similar approaches, Kim et al. (2011) and Zaman et al. (2015, 2013a, b) used AIS data as input for collision analysis spanning the Mokpo waterway in Korea and the Malacca Strait.

Mou et al. (2010) applied AIS data to study the actual behavior of ships involved in collision incidents in the Port of Rotterdam. The proposed model investigates the statistical relationship among collision incidents and ship size, speed, and course. Silveira et al. (2013) decoded, visualized, and analyzed AIS data along the coast of Portugal to estimate the collision risk associated with each route to local ports. Their model incorporates the position, course, and speed of the ships in each route to identify the collision candidates. Son et al. (2012) suggested a fuzzy algorithm to estimate collision risk among multiple ships in Korea using real-time AIS data, while Idiri and Napoli (2012) proposed a rule-based method applied to the movements of ships under changing sea conditions which would give an identification of the risks in real-time and potentially trigger an alarm to help prioritize interventions.

In Jiacai et al. 2012 used the rate of turn, the ship acceleration, and ship encounters extracted from the AIS data, in order to develop an index of dangerous areas. Similarly, in 2013, Felski and Jaskólski published six years of AIS data analysis (2006–2012) in the Gulf of Gdansk, including an investigation of dynamic fields, particularly rate of turn and heading (Felski and Jaskólski 2013). The results confirm some exceptional situations where the rate of turn and the heading data are incomplete and are thus less reliable. Xu et al. (2014) published a safety index for specific areas. They showed the utility of AIS data acquired in real-time to determine the degree of safety of the waters, instead of using traditional, static statistical analysis. Zaman et al.'s study in 2015 of the Malacca Strait included a Formal Safety Assessment (FSA) in order to determine the probability of collisions. Olindersson et al. 2015 conducted a similar study about risks in a traffic separation scheme in Bornholmsgat, Sweden. In their study, 24 hours of AIS data were utilized to assess if and how the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) were followed based on patterns from the data. The results indicated that even if the COLREGs were followed reasonably well, the minimum distance remaining to maneuver was too small. Zhang et al. 2015 also investigated a method using the AIS data to detect situations of ship-ship near collisions. Earlier work by Stitt (2004) was also concerned about the impact of the AIS on the COLREGs, but noted that AIS was a supplementary tool for mariners to execute their obligations.

Modeling and simulation are crucial in safety research; correspondingly, most of the publications found starting in 2007 until 2016 model the probability of grounding and collision in specific waters, such as the Gulf of Finland, and Madura strait (Asmara et al. 2015), and use algorithmic approaches to determine the areas of higher collision risks (Xiang et al. 2013). AIS data have been used to demonstrate, for example, that avoidance maneuvers are operated too late or that (in some cases) the intensity of traffic does not alone increase the probability of grounding. Mestl et al. 2016 used particular fields (e.g., rate of turn) in the AIS data in order to identify and characterize potentially unsafe situations.

Research into ship groundings using AIS data is generally similar to collision-related studies, in that a focus on quantitative risk models for estimation is pervasive. Pedersen (2010) used AIS data to simulate traffic to reduce the risk of grounding, ship-ship collisions, and grounding and collisions with fixed structures. As far as machine learning and statistical analysis are concerned, Koromila et al. (2014) developed a Bayesian Belief Network model using ship type, size, age, and flag extracted from AIS data. Their model targeted estimation of the probability of collision and grounding incidents in the Aegean Sea. Mazaheri et al. (2015) used AIS data to investigate the statistical relationship among grounding incidents, and density and distribution of traffic in Gulf of Finland.

3.2 Traffic simulation

Aarsæther and Moan (2009) used AIS to downscale and simulate individual maneuvers of ships to better simulate shipping traffic and associated risks. This work followed a prior publication in 2007 (Aarsaether and Moan 2007) on maneuvering and AIS data more generally. Mølsted et al. (2012) applied a similar approach with AIS data to estimate frequencies of ship accidents and the influencing factors in the Fehmarbelt area. Their model was incorporated into a risk assessment software called “ShipRisk.” Xiao et al. (2012) simulated shipping traffic patterns using AIS data in a narrow waterway (the port of Rotterdam) and a wide one (Yangtze River close to the Su-Tong bridge in China) to analyze and compare lateral positions, speed, heading, and interval times for different types and size of ships and to better understand marine traffic-associated risks. In a similar, small-scale, modeling effort, Kappel et al. (2012) used AIS to describe vessels’ impacts as one component in the assessment of overall human impact on the coastal ecosystem of Massachusetts. At a more holistic level, in the Canadian Year-Round Shipping Traffic Atlas (Canada 2014), a long time-series AIS dataset is utilized to simulate/infer shipping traffic volumes spanning all Canadian waters with a general aim to inform ecosystem research in these waters about shipping prevalence.

Traffic simulation based on AIS data is also used for training purposes. Last et al. (2017) recently published a paper on how real objects can be integrated into the simulators for crew training. The goal was to increase “the closeness to real-world scenarios.” They adapted an established software architecture in order to use a live feed of AIS data for each simulation.

3.3 Small craft issue

In many maritime basins, one of the major risks is the presence of small boats and pleasure craft which are not obligated to carry AIS. In 2014, the maritime university in Gdynia published an article about the effects of the AIS on the safety in the Gulf of Gdansk in Poland (Stupak 2014). In this work, Stupak exposes the risks of collision between large ships and yachts, illustrating how limited the radar echo is when reflected from small craft. Installing AIS Class B devices on small craft allows larger ships to have a better understanding of their surroundings, and therefore increases the safety of crew, passengers, and cargoes. A similar conclusion was published in 2012 by Bošnjak et al. 2012, explaining that the AIS, while being a good technology, is not enough to limit the risk of collisions because the system is not mandatory for all vessels. Other sensitive areas are concerned with small vessels, as is the case of the Canadian Arctic and the Arctic in general, now that various passages can remain open during the summer as a result of decreasing ice extent. However, we did not locate any peer-reviewed publications on the monitoring of small boats in the Arctic.

4 Security applications

For improved coastal security, local, state, and federal authorities and agencies require an up-to-date awareness of where, within a certain area of interest (ports approaches for example), all ships are, who they are, what type of cargoes they carry, and where they are going. Such improved information can help in a myriad of ways, for improved incident prevention and/or response. Tetreault, from the United States Coast Guard, in 2005 gave a good overview on how critical the AIS has become for coast guard missions and especially for Maritime Domain Awareness[8] (Tetreault 2005). The original concept concerns the monitoring of all the activities at sea that can have an impact on the safety, security, environment, and economy of the USA. However, in practice, concepts such as Maritime Domain Awareness (Creech and Ryan 2003; Tunaley 2013) and/or Maritime Situational Picture are commonly linked with the security applications of AIS and satellite-based AIS data gathering, integration, and analysis. From the simple shore-to-ship and ship-to-ship transponder with a limited range (and thus a limited coverage) originally envisaged, AIS data now collected via satellite capture of the signal spans a global scale, with near real-time reporting, to provide a continuous maritime picture.

In terms of peer-reviewed publications mixing security and AIS data, there are relatively few; most of the publications we were able to find are reports, proceedings, and conference papers. Moreover, the techniques used are typically published initially under other fields: visualization, simulation, pattern analysis, data fusion, tracking, etc. While security represents the end goal for many AIS applications, the research community frequently considers their work to fall within technical fields, and not on security per se. That being said, we found publications from West et al. (2010) and from the Joint Research Center of the European Commission (JRC) and FFI, published between 2011 and 2016, on counter-piracy and the statistical analysis of tracking data, pointing out the pros and the cons of using AIS.

4.1 The example of counter-piracy

Starting in 2005–2006, pirate attacks off the coast of Somalia and, subsequently, in the Gulf of Aden increased significantly. Several task forces and international

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[8] MDA or Maritime Domain Awareness is an analog to the European term Maritime Situational Awareness (MSA).

patrols were established (CTF 151, NATO, and Atalanta) in order to fight piracy and to limit the disturbance to global vessel traffic. Towards a similar end, the “Internationally Recommended Transit Corridor” (IRTC) was established in the Gulf of Aden in February 2009. However, pirates adapted their modus operandi and started to attack further from the coast of Somalia, and further into the Indian Ocean. In 2010, West et al. described how the analysis of AIS data is useful for counter-piracy operations. The AIS has been used to characterize the traffic density, patterns according to the type of ship, speed, etc. In this paper, they decided to focus on destination analysis using a phonetic algorithm. The idea is twofold: (1) help develop threat assessment for ships traveling to a common destination, and (2) help guide patrols escorting ships in complex or vast areas at vulnerable times of the day. However, as Vespe et al. 2015) recalled in their paper, an AIS can be lawfully switched off in special areas where the security is threatened, at the discretion of the ship captain, potentially leading to incomplete datasets. For this reason, long-range identification and tracking (LRIT) system data may provide a more definitive data source to track these ships (Posada et al. 2011), though it is not openly accessible and is more sparsely sampled than AIS. Nevertheless, when AIS is available, it produces the largest amount of data (Greidanus et al. 2016) and access is unrestricted. For more information, we direct the reader to the JRC-published (February 2015) user manual dealing with piracy, maritime awareness, and risk (PMAR) identifying the projects related to an assessment of tools and techniques for counter-piracy and maritime security.

4.2 Port security

Another topic which falls under maritime security is port security. However, we were unable to find peer-reviewed papers combining AIS data capture and analysis for port security purposes (perhaps due to confidentiality issues in some cases). A conference paper from 2007, presented by H. M. Tun, G. S. Chamers, T. Tan, and T. Ly and dedicated to port intelligence and AIS, has been cited, but we have not been able to locate a copy for consideration; thus, we cannot attest to the value nor the relevance of this paper to our review.

5 AIS analysis techniques and technology

This section is dedicated to analytical techniques involving AIS, and we present them as four distinct research fields: (1) the satellites and constellations available, (2) data integration from multiple sources, (3) the analysis of the data, and (4) the quality of AIS services in dense-traffic areas, wide maritime areas, and high-latitude areas. However, if the reader is looking for a more technical review of AIS algorithms, models, predictions, and so on, the most comprehensive and complete survey that we located was published in 2016 by Tu et al. from the Nanyang Technical University in Singapore. This survey rates the quality of data from the commercial providers and from open sources and compares the anomaly detection algorithms, route estimation models, collision prediction, and path-planning approaches.

5.1 Satellites

The use of small satellites (incl. micro-, nano-, pico-) is not new, although growth has been exploding the last decades for a variety of applications (Guerra et al. 2016). As far as the AIS receivers onboard small satellites, the first publications we found dated back to 2001. These comprise mainly technical reports and conference presentations; however, most of them have been translated into peer-reviewed publications.

A publication from FFI, dated from 2005, describes the roles that the small satellites were envisioned to play in maritime surveillance (Wahl et al. 2005)[9] and specifically in high latitudes (their area of interest including Jan Mayen and Svalbard). Small satellites are cheaper to develop and deploy and, therefore, are more accessible for emergent countries and smaller nations desiring to improve their maritime surveillance capabilities. In this 2005 publication, the authors introduced the possibility of having an AIS receiver on a microsatellite in low Earth orbit (LEO), where the main issues would be large footprint (relative to the AIS specification) and signal interference. In 2006 and 2008, FFI published the results of their feasibility study (Eriksen et al. 2006; Hoye et al. 2008), expecting close to 100% detection. Their simulations and analyses showed that the AIS signal, captured from space, would generate much better information which could serve to significantly improve safety at sea by increasing the number of ships for which it would enable detection, tracking, and monitoring. In 2010, they presented the first results in the first month of operation for AISSat-1 and the NORAIS receiver (Eriksen et al. 2010), for applications such as global traffic monitoring, fisheries protection, and counter-piracy.

A comprehensive survey on small satellites and their roles for oceanography purposes was published by Guerra et al. in 2016, in which they detail the advantages of using small satellites (lower costs, less time to be build, faster data return, more missions, flexibility, among other topics), and the different types of missions they are used for. Within the survey, Section 3.3 in particular deals with AIS and ship tracking.

5.2 Data fusion

Data fusion in the AIS context primarily concerns ship detections extracted from satellite imagery and compared with AIS tracks and VMS, LRIT, and radar. Having a complete and accurate surface picture relies also on the capacity to predict ship positions in order to compensate for delays, deviations from the planned route, or incomplete data. Research groups in Italy, Germany, Norway, Canada, and France and industries attached to defense and space agencies have been working since 2004 on this topic and its sub-categories. Supranational agencies like the European Commission, NATO, and the UN are extremely interested and committed to these works as they are used for improving and enhancing safety and security. Even though the paper is not solely dedicated to the application of data fusion for maritime surveillance, the only recent state-of-the-art review found, published in 2011 by Khaleghi et al. 2011, summarizes methodologies, developments, and emerging trends for multi-sensor data fusion as a field of research.

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[9] They presented some results earlier at conferences starting in 2001 and 2003.

Multi-sensor integration is necessary to develop the most accurate maritime picture at coastal and open-sea scales (Vespe et al. 2008; Guerriero et al. 2008; Posada et al. 2011; Eriksen et al. 2014; Greidanus et al. 2016), and data fusion methods have generally provided satisfactory performance. However, data correlation quality can be a major concern in high-density areas (Zhao et al. 2014).

In this process, several authors have been and are still investigating geo-visualization methods in order to support spatio-temporal analyses and improve decision-making (Vatin and Napoli 2013). The studies at basin-wide scale made by the JRC and FFI (Posada et al. 2011; Eriksen et al. 2014; Greidanus et al. 2016) show that the desired performance results can be reached by modulating the number of satellites or data sources used during an operation. In 2015, (C-CORE 2015) a Canadian company based in St. John's Newfoundland, published a report for DRDC (Defence Research and Development Canada), which was dedicated to a review of AIS and synthetic-aperture radar (SAR) data fusion algorithms, along with a comparison of their performance. This review appears to be the only recent, critical, and comprehensive analysis of the existing literature in terms of AIS-SAR association for maritime surveillance purposes. Their introduction mirrors our limited findings in terms of papers presenting algorithms specifically on AIS and SAR data and their classification of the existing algorithms is more readily digested than the one chosen by Abielmona et al. (2014). Moreover, their evaluation was made in the context of use conjoint with the RADARSAT Constellation Mission (RCM). The main idea put forth was to determine the best conditions and what performance should be achieved for AIS-SAR synchronized acquisitions. Pursuant to this study, the Canadian Space Agency (CSA) issued a request for proposal (RFP) in February 2016 regarding Feasibility Studies for the Development of Space-Based Automatic Identification System Applications for the Canadian Space Agency. The (six) studies address the following problem: "improving the identification and monitoring of vessels in the maritime operations context through the use of Space-Based Automatic Identification Systems (S-AIS) data in conjunction with Earth Observation (EO) imagery".

5.3 Pattern analysis, traffic density, and anomaly detection

AIS data are used for movement prediction, visualization of vessel traffic densities, and movement/mobility patterns. These are full fields of research, primarily used for anomaly detection. For a general view of what anomaly detection is, we recommend the general review of relevant techniques published in 2009 by Chandola et al. The paper produces the first comprehensive overview of the general techniques across many fields of application. For a broad view of recent trends, research, and challenges, the presentation published in 2017 by Claramunt et al. 2017 gives a good overview in terms of analysis and data integration for the monitoring of maritime activities. In particular, parts 3 and 4 are dedicated to event detection, visual analytics, and forecasting system in support of decision-making.

Based on the large number of articles and conference papers we found in this domain, we decided to categorize a selected bibliography according to (1) automated reasoning tools, (2) pattern analysis, and (3) visual analytics.

5.3.1 Automated reasoning tools

During a project on exploitation of collaborative knowledge for Maritime Domain Awareness, DRDC published a review of anomaly detection techniques (Martineau and Roy 2011). The need for detecting anomalous patterns “has been identified by operators/analysts as an important aspect requiring R&D” (Martineau and Roy, p. 7). Traditional monitoring and traditional data gathering mostly focused on following legitimate activities, and few projects or existing platforms had focused on abnormal behaviors. Detecting anomalies is a demanding task. That being said, there is still no consensus on what maritime anomaly detection is; however, for most users and applications in the maritime world, an anomaly corresponds to unusual behavior that may be associated with a potential threat. In a paper published in 2010, Roy talked about the importance of having automated reasoning tools, capable of helping the operators and analysts dealing with the large volume of data and information they receive (Roy 2010). The main purpose of these “intelligent” systems, as he calls them, infer the necessary facts and eventually give alerts or alarms on situations that necessitate an intervention. Prior to this, Roy had also published a good overview of anomaly detection in the maritime domain in 2008 (Roy 2008) and especially of the spatial ontology used to identify anomalous behaviors, as did Vandecasteele and Napoli in 2012.

Morel and Claisse 2010 presented a European project (I2C)[10] aiming at creating and implementing alarms in integrated systems dedicated to maritime surveillance. These alarms would be based on rules, defined through the analysis of abnormal behaviors, abnormal activities, and abnormal conditions. The main challenges as described by the authors are twofold: (1) how to define the rules? and (2) how to apply the rules? The topic of rules is not new nor are the challenges described by Morel and Claisse. Previously, Nilsson et al. (2008) discussed a prototype of a rule-based expert system application introduced in 2006 (Edlund et al. 2006) and that they reassessed taking into account expert knowledge. Based on users’ requirements and after trial sessions, they highlighted how important the participation of the users (operators/analysts) was in terms of identifying the gaps and knowledge transfer, and in documenting the rules’ justification. They also highlighted the importance of fusion techniques when developing rule-based systems. Ray et al. 2013 gave a good overview of the preceding work on rule-based systems and added a bit more flexibility to the existing approaches. The flexibility comes from the incorporation of top-down and bottom-up approaches in the system, an addition not considered in the previous methodologies. Notably, the system described also allowed for the definition of spatial rules.

5.3.2 Data mining/pattern analysis

Using data mining principles, Etienne et al. 2012 and Devogèle et al. 2013, showed how maritime data, and especially AIS, can be processed and analyzed in a way that will help qualifying a position and/or a trajectory. Lecornu et al. 2013 proposed an approach to estimate the degree of reliability assigned to missing segments of a vessel trajectory. This is an interesting supplement as most existing analyses only take into account full segments and reject incomplete ones. This work refers to previous analyses

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[10] http://en.sofresud.com/Maritime-Surveillance/Vessels-Real-Time-Database/I2C

presented by Etienne et al. in 2010 and 2012, as well as Redoutey et al. 2008. In terms of pattern discovery and anomaly detection using AIS data, Pallotta et al. (2013), published under the framework of NATO, a methodology called TREAD (Traffic Route Extraction and Anomaly Detection). This methodology was developed to be used in decision support platforms or tools, without distinction of the "levels of intermittency,[11] persistence and data sources[12]."

5.3.3 Visual analytics

Visualization is crucial for effective shipping data analysis; authors like Andrienko and Riveiro describe it as a way to enhance user perception and to get better analysis by integrating multi-sensor data sets with human expert knowledge (Riveiro et al. 2008, 2009, 2011; Andrienko et al. 2016). In 2009, Riveiro et al. introduced a tool called VISAD, an interactive tool designed to support the processing of maritime shipping data, the identification of anomalous behavior, and detection of rare events. Another paper proposes an interesting third section dedicated to some relevant publications where visualization had been used to enhance anomaly detection and acknowledges the scarcity of literature regarding the use of anomaly detection methods in real environments or human factors studies (Riveiro and Falkman 2011). An interesting part of Riveiro et al.'s work lies in the re-integration of the human factor and the need for expert knowledge. However, Vatin and Napoli presented in 2013 a critique of previous publications as being limited in terms of needs that the developed platforms could meet. They explain how diverse the needs of the operators are for maritime surveillance and how generally one interface can answer very specific needs but would not be useful for other operators. They also take into account the human factor, explaining how the background or profile of an analyst would affect the understanding and the manipulation of the visualization tool. Vatin and Napoli proposed a methodology combining the power of visual analytics with the most actors possible in the system by taking into account the users' acceptance of technology, their background, and their requirements. The expected output was a library of visual analytics environments that could satisfy the needs of several users. Pursuing this work further, Vatin et al. introduced in 2014 a model aggregating adequate visualization methods, human factors, ontologies (Vandecasteele and Napoli 2012a, b; Vatin et al. 2014), known dangerous patterns, and ship behavior models.

In 2016, Andrienko et al. presented the importance of visual analytics by using a case study based in the bay of Brest, France. For the purpose of their study, they used a large AIS dataset and extracted and visualized the spatial distribution of anomalous events by means of various filters. The book published by Andrienko et al. in 2013 is a recommended source for readers interested in movement and visual analytics in general.

Without specifically mentioning visual analytics or AIS data,[13] previous authors like Popovich et al. 2006, 2009 Petit et al. 2006, and Claramunt et al. 2007 demonstrated the importance of visualization and the importance of intelligent geographic

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[11] See the previous paragraphs on rule-based systems, as well as Section 5.4 on data quality assessment.

[12] See Section 5.2 on data fusion.

[13] VTCS integrate AIS data. The papers do not speak about AIS specifically but are important in terms of integration of information and in terms of visualization for supporting the decision-making process.

information system (IGIS) and how they can be integrated in maritime surveillance, and vessel traffic control systems (VTCS)[14], in order to enhance the decision-making process.

5.4 Data quality assessment

One trend that emerged with satellite-based AIS is data quality assessment. Although it seems to be increasing in conjunction with the concept of big data, human errors have interested researchers since the beginning of analytical use of AIS (Creech and Ryan 2003; Baldauf et al. 2008). This topic is linked to research on risks and crises, as the AIS data stream can be misused or spoofed (Katsilieris et al. 2013; Windward 2014; Ray et al. 2015, 2016; Iphar et al. 2015a, b and 2016a, b, c), errors can be unintentionally entered, and the system can experience failure on its own. For example, the global navigation satellite system (GNSS) coordinates are an identified weak point in the AIS message. A goal of these data quality-oriented publications is to help decision-making in case of a crisis. Iphar et al. for example were inspired by information theory, developed by Shannon at the end of the 1940s, in order to assess the integrity of data. They have appeared in recent conferences (2016), asserting that the integrity must be assessed for one message or for a group of messages. Iphar has continued to develop this work by using data mining and data clustering methods for anomaly detection, introducing a methodology to discover falsified messages using a combination of raw messages and post-processing techniques on these messages.

Most of the mistakes cited are human errors when entering text and are thus unintentional. Junzhong's thesis, published in 2004, stressed the lack of training for AIS usage and the corresponding impact on maritime safety. The author proposed a syllabus for operators, as there are no IMO conventions, regulations, or guidelines on AIS training. Several texts refer to this issue but only in passing. In 2007, Harati-Mokhtari and Wall published on the human factors in maritime accidents. They studied several AIS message types, noting errors and identifying the level of failures and the proportion due to human factors. To our knowledge, this study was never followed up on when satellite AIS emerged. It would be interesting to see if the same fields are subject to the same percentage of human error, considering the satellite component, but also the longer period since AIS' adoption. In 2012, Felski and Jaskólski worked on the availability of AIS and on information unfitness (Felski and Jaskólski, 2012b, c); in this same year (2012), Bošnjak et al. 2012 published a paper on how to help the seafarer to get acquainted with the system as, for users, the quality of the data depends on seafarer's ability to recognize errors.

The first publications concerning the feasibility of a satellite-based AIS (circa 2004) were also concerned with the quality assessment and how to improve the messages, avoiding the messages collision, the reception, etc. In 2013, DRDC published a report (C-CORE 2013) on the performances of the S-AIS attached to the RCM. In this project, they simulated the S-AIS data and developed an algorithm capable of evaluating the performance of the system for ship detection based on previous analyses made and

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[14] VTS should be used instead of VTCS as this is the official IMO name, referring to SOLAS V/12 and Res.A.587(20), and in the IALA VTS Manual. However, the papers being specific about VTCS we do not judge useful to change the word used by the authors.

published by FFI, Tunaley, and the International Telecommunication Union (ITU). They showed that using de-collision techniques in high-density areas increases the probability of ship detection.

Greidanus et al. in 2013, and Eriksen et al. in 2014, developed a clearer view of the complementarity of various tools for maritime domain awareness. In 2013, Greidanus et al. gathered data from different ship reporting systems at a basin-wide scale (the Horn of Africa), and compared them. Their study was applied to a particular goal of maritime surveillance: counter-piracy. They illustrated that with five to six satellites used complementarily, the quantity of new ships detected (MMSI) levels off, but the maritime picture can be maintained. Limitations included a note that other systems in use have a more accurate picture, and that detections made by SAR revealed that 50% of the vessels are not reporting. These limitations need to be further researched to address ships are too small to carry AIS. In 2014, Eriksen et al. published the results of a second campaign in the Gulf of Guinea. Adding one or two AIS data providers in the region increased the number of ships detected by 384 and 31 respectively.

Currently, Salmon et al. are working on hybrid queries for both streaming and offline data, in order to identify the maritime regions covered by AIS vs. ones that are not. In 2015 and 2016, they introduced specific queries called “black holes” to help maritime authorities in terms of coverage affecting regulations, maintenance and installation decisions, etc. (Salmon et al. 2015, 2016)

6 Conclusions and perspectives

This review presented many examples of the widespread use of the automatic identification system (AIS) since its introduction by the IMO until the present. The protocol and its resulting data have proven to be practical and useful for activities ranging from basic traffic management, strategic planning, simulation-based training, analysis of various risks in terms of human, environmental, and economic loss, to decision-making in the contexts of safety and security at sea; remarkably, at the beginning of the AIS implementation, researchers and operators wondered about the effectiveness of AIS for fulfilling its stated mandate. The publications reviewed have one major point in common—that the information service depends heavily on the quality of AIS information and intelligent applications for information processing, integration, and presentation. In this context, it has also been demonstrated that AIS alone has never been sufficient to describe a full, comprehensive maritime picture. In 2003, Creech and Ryan recommended, for national security, the use of multiple technologies that would complement each other and that a satellite-borne system would be necessary. However, AIS has the advantage of producing the largest volume of ship position data and it is commercially or open-source accessible, which is not the case for other automatic ship position reporting systems (LRIT, VMS, etc.).

However, the AIS still faces challenges, both in its operational use and in its broader application. A key challenge shared across all uses is that of data quality/data entry error rate; the value of the system is limited to the quality of the information which it can provide. In particular, elements of the system which require user input (vessel particulars, destination, etc.) suffer from widespread data entry errors, limiting their utility. Operator training, which was not introduced in parallel with the system, may aid in remedying this issue. External, open registries of vessel particulars could also be used to alleviate some of the dependence on diligent operator data entry (at least for elements which are relatively static), though it would require the establishment of some authority for collecting and maintaining this information.

Carriage rules for AIS-B and small vessels do exist at national and regional levels, but with great variation internationally. This poses challenges in interpreting these data, particularly in correcting for or assessing sampling level. As well, mixed carriage rules for these smaller vessels can impact large vessel operators, who benefit from the added visibility of smaller vessels which operate AIS but cannot rely on uniform adoption across regions. Though unlikely to be forthcoming, some consensus on carriage rules for smaller vessels would likely create benefits for the system and many of its users, while acknowledging that this would also impose new costs for equipment and operation to the affected vessels' operators. In considering the use of AIS data for analytical purposes, there is still room for coverage improvement, though, admittedly, gaps in coverage are closing fast with increasing numbers of both terrestrial observing stations and AIS-capturing satellite deployments. Lastly, in considering the use of AIS data for enforcement purposes, whether for collision regulation (COLREG) conformance, marine protected area (MPA) observance, or fishing regulation concerns, among other uses, some clarification of the system's role to this end would help both operator and enforcement agencies. Prior to applying the system in these roles, it is necessary to identify the suitability (or otherwise) of the AIS data for these applications.

Globally, we found that the literature lacks papers or reports on training and feedback from the users. Any feedback is generally provided on an ad hoc basis, in presentations, proceedings, or reports. But, to our knowledge, the only formal feedback from users were from Creech and Ryan in 2003 and the Pilot's perspective in 2004 (Pratt and Taylor 2004). Moreover, we know that for some of the research projects, users' requirements and feedback are investigated. It would be valuable to have a scholarly paper presented on the evolution of germane maritime requirements and the solutions provided by the AIS and other techniques.

Based on our review, we generated a publicly accessible bibliography in which we gathered a selection of the papers to have/read on the AIS applications. The library has been developed with the open-source Zotero Software[15] and will be accessible soon.

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[15] https://www.zotero.org/

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Affiliations

Mélanie Fournier[1,2] · **R. Casey Hilliard**[3] · **Sara Rezaee**[1] · **Ronald Pelot**[1]

R. Casey Hilliard
casey.hilliard@dal.ca

Sara Rezaee
sara.rezaee@dal.ca

Ronald Pelot
ronald.pelot@dal.ca

[1] Department of Industrial Engineering, MARIN, Dalhousie University, Morroy Building 5269 Morris St., Halifax, Nova Scotia, Canada

[2] Eysins, Switzerland

[3] DAL Goldberg CS Building R449, Halifax, Nova Scotia, Canada